

## METHOD AND APPARATUS FOR FORCE BALANCING OF A CORIOLIS FLOW METER

**Background of the Invention**5    1. *Field of the Invention*

The present invention relates to force balancing of a Coriolis flow meter.

2. *Statement of the Problem*

10       Vibrating conduit sensors, such as Coriolis mass flow meters, typically operate by detecting motion of a vibrating conduit that contains a material. Properties associated with the material in the conduit, such as mass flow, density and the like, in the conduit may be determined by processing signals from motion transducers associated with the conduit, as the vibration modes of the vibrating material-filled system generally are affected by the combined mass, stiffness and  
15       damping characteristics of the containing conduit and the material contained therein.

      A typical Coriolis mass flow meter includes one or more conduits that are connected inline in a pipeline or other transport system and convey material, e.g., fluids, slurries and the like, in the system. Each conduit may be viewed as having a  
20       set of natural vibration modes including, for example, simple bending, torsional, radial and coupled modes. In a typical Coriolis mass flow measurement application, a conduit is excited in one or more vibration modes as a material flows through the conduit, and motion of the conduit is measured at points spaced along the conduit. Excitation is typically provided by an actuator, e.g., an  
25       electromechanical device, such as a voice coil-type driver, that perturbs the conduit in a periodic fashion. Mass flow rate may be determined by measuring time delay or phase differences between motion at the transducer locations.

      The magnitude of the time delay is very small; often measured in nanoseconds. Therefore, it is necessary to have the transducer output be very  
30       accurate. Transducer accuracy may be compromised by nonlinearities and asymmetries in the meter structure or from motion arising from extraneous forces. For example, A Coriolis mass flow meter having unbalanced components can vibrate its case, flanges and the pipeline at the drive frequency of the meter. This vibration perturbs the time delay signal in an amount that depends on the rigidity of

the mount. Since the rigidity of the mount is generally unknown and can change over time and temperature, the effects of the unbalanced components cannot be compensated and may significantly affect meter performance. The effects of these unbalanced vibrations and mounting variations are reduced by using flow meter designs that are balanced and by using signal processing techniques to compensate for unwanted components of motion.

The balanced vibration discussed above involves only a single direction of vibration: the Z-direction. The Z-direction is the direction that the conduits are displaced as they vibrate. Other directions, including the X-direction along the pipeline and the Y-direction perpendicular to the Z and X-directions, are not balanced. This reference coordinate system is important because Coriolis flow meters produce a secondary sinusoidal force in the Y-direction. This force creates a meter vibration in the Y-direction that is not balanced, resulting in meter error.

One source of this secondary force is the location of the mass of the meter driver assembly. A typical driver assembly consists of a magnet fastened to one conduit and a coil of conductive wire fastened to another conduit. The Y-vibration is caused by the center of mass of the driver magnet and the center of mass of the driver coil not lying on the respective X-Y planes of the centerline(s) of the flow conduit(s). The X-Y planes are necessarily spaced apart to keep the conduits from interfering with one another. The centers of mass of the magnet and/or coil are offset from their planes because the coil needs to be concentric with the end of magnet to be at the optimum position in the magnetic field.

A flow conduit, when driven to vibrate, does not truly translate but rather cyclically bends about the locations at which it is fixed. This bending can be approximated by rotation about the fixed point(s). The vibration is then seen to be a cyclic rotation through a small angle about its center of rotation, CR. The angular vibration amplitude is determined from the desired vibration amplitude in the Z direction and the distance,  $d$ , from the center of rotation of the conduit center at the driver location. The angular amplitude of vibration,  $\Delta\theta$ , is determined from the following relation:

$$\Delta\theta = \arctan (\Delta Z/d) \quad (1)$$

The offset of the driver component (magnet or coil assembly) center of mass from the conduit centerline causes the driver component center of mass to have a Y-component of its vibration. The driver component mass usually has an offset in the Z-direction that is at least equal to the conduit radius. The angular offset,  $\Phi$ , from the conduit centerline is thus not negligible. The driver component mass oscillates about its offset position with the same angular amplitude as the flow conduit,  $\Delta\theta$ . Approximating the motion of the driver mass as being perpendicular to the line connecting the driver center of mass with the center of rotation, CR, the driver mass Y-direction motion,  $\Delta Y_m$ , can be solved from the following:

$$\Delta Y_m = \Delta Z \sin (\Phi) \quad (2)$$

The Y-direction motion of the driver component mass causes the whole meter to vibrate in the Y-direction. Conservation of momentum requires that, for a freely suspended meter, the Y-direction vibration of the entire meter is equal to the Y-direction vibration amplitude of the driver mass times the ratio of the driver mass divided by the meter mass. This Y-vibration of the entire meter is a direct result of the desired conduit vibration in Z in conjunction with the angular offset of the drive components' centers of mass. This coupling between the desired conduit vibration and the undesired Y-vibration of the entire meter means that damping of the meter Y-vibration damps the flow conduit vibration in Z, and that a stiff meter mount raises conduit frequency while a soft meter mount lowers conduit frequency. The change in conduit frequency with mounting stiffness has been observed experimentally in meters with high Y-vibration amplitude. It is a problem because conduit frequency is used to determine fluid density and frequency is also an indication of conduit stiffness. Changes in conduit stiffness due to mounting stiffness change the calibration factor of the meter. The direct coupling between the drive vibration and the local environment also results in an unstable zero (a flow signal when no flow is present) of the meter.

### Summary of the Solution

The present invention helps solve the problems associated with unbalanced vibrational forces using a balance system that is sized and located so as to balance out the drive system.

Some examples of a balance system include a Y-balance mass placed on the opposite side of a flow conduit as a driver component. The balance mass is sized and located such that the combined center of mass of the driver plus the Y-balance mass lies on the X-Y plane of the conduit centerline.

5           In some examples, a balance device called an active-y-balance can be configured on the flow conduit(s). The active-y-balance consists of a mass connected to one end of a leaf spring with the other end attached to the flow conduit proximate the driver. Active-y-balances can be used on one or both conduits depending on the locations of the mass centers of the magnet and coil  
10           and the type of flow meter configuration (i.e. single or dual conduits).

          The active-y-balance works by using the Z-direction conduit motion to move the active-y-balance mass in the Y-direction. The Y-direction momentum of the active-y-balance can be designed to balance the Y-direction momentum of the drive components and to thereby prevent case and environment shaking. By the  
15           principle of equivalence, this also makes the meter immune to environmental vibrations and damping.

#### ASPECTS

An aspect of the invention is a Coriolis flow meter comprising:

          at least one flow conduit;  
20           a drive system coupled to the at least one flow conduit;  
          a balance system coupled to the at least one flow conduit; wherein the balance system is sized and located such that the momentum of the balance system is equal and opposite to the momentum of the drive system.

          Preferably said balance system comprises a balance mass.  
25           Preferably said balance system is sized and located such that the combined center of mass of the drive system and the balance system lies proximate a plane of the centerline of the at least one flow conduit.

          Preferably said balance system comprises a balance mass coupled to the at least one flow conduit using a leaf spring.

30           Preferably said leaf spring stiffness and the balance mass cause the natural frequency of the balance system to be less than the drive frequency of the flow meter.

          Preferably said balance system vibrates out of phase with the at least one flow conduit.

Preferably said balance system is located on the opposite side of the at least one flow conduit from the drive component and at an orientation substantially forty-five degrees to a plane of the flow conduit.

5 Preferably said balance system is located on the opposite side of the at least one flow conduit from the drive component.

Preferably said balance system is sized and located such that the momentum of the balance system is equal and opposite to the momentum of the drive system in a direction perpendicular to a drive motion.

10 An additional aspect of the invention is a method for force balancing a Coriolis flow meter having at least one flow conduit, the method comprising the steps of:

coupling a drive system to the at least one flow conduit;

coupling a balance system to the at least one flow conduit; and

locating and sizing the balance system such that the momentum of the balance system is equal and opposite to the momentum of the drive system.

15 Preferably said method includes the step of forming the balance system using a balance mass.

20 Preferably said method further comprises the steps of locating and sizing the balance system such that the combined center of mass of the drive system and the balance system lies proximate a plane of the centerline of the at least one flow conduit.

Preferably said step of coupling a balance system to at least one flow conduit comprises the steps of coupling a balance mass to at least one flow conduit using a leaf spring.

25 Preferably said method includes the step of choosing the leaf spring stiffness and the balance mass such that the natural frequency of the balance system is below the drive frequency of the flow meter.

Preferably said method includes the step of vibrating the balance system out of phase with the at least one flow conduit.

30 Preferably said step of locating the balance system comprises the steps of: locating the balance system on the opposite side of the at least one flow conduit from the drive system; and

orientating the balance system substantially forty-five degrees to a plane of the flow conduit.

Preferably said method includes the step of locating the balance system on the opposite side of the at least one flow conduit from the drive system.

Preferably said step of locating and sizing the balance system comprises the steps of locating and sizing the balance system such that the momentum of the balance system is equal and opposite to the momentum of the drive system in a direction perpendicular to a drive motion.

#### Description of the Drawings

FIG. 1 illustrating a Coriolis flow meter;

FIG. 2 illustrating a driver of a Coriolis flow meter;

10 FIG. 3 illustrates an X-axis section view of a flow conduit of a Coriolis meter;

FIG. 4 illustrates a balance system in a first example of the invention;

FIG. 5 illustrates a balance system in another example of the invention.

#### Detailed Description of the Invention

**FIGS. 1-5** and the following description depict specific examples to teach those skilled in the art how to make and use the best mode of the invention. For the purpose of teaching inventive principles, some conventional aspects have been simplified or omitted. Those skilled in the art will appreciate variations from these examples that fall within the scope of the invention. Those skilled in the art will appreciate that the features described below can be combined in various ways to form multiple variations of the invention. As a result, the invention is not limited to the specific examples described below, but only by the claims and their equivalents.

**FIG. 1** illustrates a Coriolis flow meter **5** comprising a flow meter assembly **10** and meter electronics **20**. Meter electronics **20** is connected to meter assembly **10** via leads **100** to provide density, mass flow rate, volume flow rate, totalized mass flow, temperature, and other information over path **26**. It should be apparent to those skilled in the art that the present invention can be used by any type of Coriolis flow meter regardless of the number of drivers, pick-off sensors, flow conduits or the operating mode of vibration.

Flow meter assembly **10** includes a pair of flanges **101** and **101'**; manifolds **102** and **102'**; driver **104**; pick-off sensors **105-105'**; and flow conduits **103A** and **103B**. Driver **104** and pick-off sensors **105** and **105'** are connected to flow conduits **103A** and **103B**.

Flanges **101** and **101'** are affixed to manifolds **102** and **102'**. Manifolds **102** and **102'** are affixed to opposite ends of spacer **106**. Spacer **106** maintains the

spacing between manifolds **102** and **102'** to prevent undesired vibrations in flow conduits **103A** and **103B**. When flow meter assembly **10** is inserted into a pipeline system (not shown) which carries the material being measured, material enters flow meter assembly **10** through flange **101**, passes through inlet manifold **102** where  
5 the total amount of material is directed to enter flow conduits **103A** and **103B**, flows through flow conduits **103A** and **103B** and back into outlet manifold **102'** where it exits meter assembly **10** through flange **101'**.

Flow conduits **103A** and **103B** are selected and appropriately mounted to inlet manifold **102** and outlet manifold **102'** so as to have substantially the same  
10 mass distribution, moments of inertia, and elastic modules about bending axes **W--W** and **W'--W'** respectively. The flow conduits extend outwardly from the manifolds in an essentially parallel fashion.

Flow conduits **103A-B** are driven by driver **104** in opposite directions about their respective bending axes **W** and **W'** and at what is termed the first out of  
15 bending mode of the flow meter. Driver **104** may comprise one of many well known arrangements, such as a magnet mounted to flow conduit **103A** and an opposing coil mounted to flow conduit **103B**. An alternating current is passed through the opposing coil to cause both conduits to oscillate. A suitable drive signal is applied by meter electronics **20**, via lead **110** to driver **104**. The description of **FIG. 1** is  
20 provided merely as an example of the operation of a Coriolis flow meter and is not intended to limit the teaching of the present invention.

Meter electronics **20** transmits sensor signals on leads **111** and **111'**, respectively. Meter electronics **20** produces a drive signal on lead **110** which causes driver **104** to oscillate flow conduits **103A** and **103B**. Meter electronics **20**  
25 processes left and right velocity signals from pick-off sensors **105**, **105'** to compute mass flow rate. Path **26** provides an input and an output means that allows meter electronics **20** to interface with an operator.

**FIG. 2** illustrates a drive system **104** for a preferred embodiment of Coriolis flow meter **5**. In a preferred exemplary embodiment, driver **104** is a coil and magnet assembly. One skilled in the art will note that other types of drive systems may be  
30 used.

Driver **104** has a magnet assembly **210** and a coil assembly **220**. Brackets **211** extend outward in opposing directions from magnet assembly **210** and coil assembly **220**. Brackets **211** are wings which extend outward from the flat base and

have a substantially curved edge **290** on a bottom side that is formed to receive a flow conduit **103A** or **103B**. The curved edge **290** of brackets **211** are then welded or in some other manner affixed to flow conduits **103A** and **103B** to attach driver **104** to Coriolis flow meter **5**.

5 Magnet assembly **210** has a magnet keeper **202** as a base. Brackets **211** extend from a first side of magnet keeper **202**. Walls **213** and **214** extend outward from outer edges of a second side of magnet keeper **202**. Walls **213** and **214** control the direction of the magnetic field of magnet **203** perpendicular to the windings of coil **204**.

10 Magnet **203** is a substantially cylindrical magnet having a first and a second end. Magnet **203** is fitted into a magnet sleeve (Not shown). The magnet sleeve and magnet **203** are affixed to a second surface of magnet keeper **202** to secure magnet **203** in magnet assembly **210**. Magnet **203** typically has a pole (not shown) affixed to its second side. The magnet pole (not shown) is a cap that is fitted to the  
15 second end of magnet **203** to direct the magnetic fields into coil **204**.

Coil assembly **220** includes coil **204**, and coil bobbin **205**. Coil bobbin **205** is affixed to a bracket **211**. Coil bobbin **205** has a spool protruding from a first surface around which coil **204** is wound. Coil **204** is mounted on coil bobbin **205** opposing magnet **203**. Coil **204** is connected to lead **110** which applies alternating currents to  
20 coil **204**. The alternating currents cause coil **204** and magnet **203** to attract and repel one another which in turn causes flow conduits **103A** and **103B** to oscillate in opposition to one another.

**FIG. 3** illustrates a simplified X-axis section view of flow conduit **103**. Flow conduit **103** has mounted to it driver **104**. Driver **104** is offset from flow conduit **103**  
25 by  $\Phi$ . Flow conduit **103** moves in the Z-direction with an amplitude  $\Delta Z$ . As flow conduit **103** translates in the Z-direction its fixed location causes it to rotate about its center of rotation, **CR**, resulting in angular amplitude,  $\Delta\theta$ . Driver **104** and its associated center of mass, **CM**, rotates with the same angular amplitude,  $\Delta\theta$ , as flow conduit **103**. However, because of the offset angle,  $\Phi$ , drive component center  
30 of mass **CM** oscillates up and down line **L**. This gives drive component center of mass **CM** vertical motion  $\Delta Y_m$ .

**FIG. 4** illustrates a balance system **400** in a first example of the invention. Balance system **400** includes balance weights **401** & **402** coupled to flow conduits **103A** & **B**. Coupling of balance weights **401** & **402** can be accomplished using

various methods including mechanical attachment, brazing or gluing. Balance weight **401** has a center of mass  $CM_{b1}$ . Balance weight **401** is sized and located such that its center of mass  $CM_{b1}$  combined with the coil assembly center of mass  $CM_c$  results in a combined center of mass  $CCM_1$  that is located on the X-Y plane of conduit **103A**. Also, balance weight **402** has a center of mass  $CM_{b2}$ . Balance weight **402** is sized and located such that its center of mass  $CM_{b2}$  combined with the magnet assembly center of mass  $CM_m$  results in a combined center of mass  $CCM_2$  that is located on the X-Y plane of conduit **103B**. The particular attributes of the balance weights are such that the mass times velocity of the balance weight is equal and opposite to the mass times velocity of the driver assembly, in the Y-direction, for each flow conduit as shown by:

$$(M * V_Y)_{BW} + (M * V_Y)_{DA} = 0 \quad (3)$$

In other words the momentum of the balance weight counters the momentum of the driver assembly attached to a particular conduit as given by:

$$(M_{BW})_Y + (M_{DA})_Y = 0 \quad (4)$$

**FIG. 5** illustrates balance system **500** in another example of the invention. Balance system **500** includes balance weights **501** & **502** coupled to flow conduits **103A** & **B** using leaf springs **504** & **505**. Leaf spring **504** is oriented at approximately 45 degrees to the X-Y plane and is connected to the opposite side of the flow conduit as coil assembly **220**. The stiffness of leaf spring **504** and mass of balance weight **501** are chosen so that the natural frequency of the active-y-balance in its first vibration mode (the diving board mode) is below the drive frequency of the meter. With the natural frequency below the excitation (drive) frequency, weight **501** tends to move out of phase with conduit **103A**. Thus, as conduit **103A** moves to the left (-Z direction), active-y-balance weight **501** moves to the right (+Z) relative to the conduit. But, because of the angle of leaf spring **504** to the X-Y plane, weight **501** is constrained by leaf spring **504** to move to the right and down (+Z and -Y). This is advantageous because when conduit **103A** moves to the left, the offset coil assembly **220** moves left and up (+Z and +Y). By designing mass and spring rate such that the Y-direction momentum (mass times velocity) of

the active-y-balance are equal and opposite to the Y-direction momentum of the offset driver components, the external Y-direction vibration of the entire meter can be nearly eliminated. The same design principles apply to tube **103B**.

5 This second example has an additional advantage. Because weight **501** and **502** are suspended from conduits **103A & B** by leaf spring **504 & 505**, they vibrate out of phase with flow conduits **103A & B**, resulting in very little of its mass being coupled to flow conduits **103A & B**.

10 The above examples are not limited to compensating for the driver mass offset. For instance, deformation of the manifold castings by conduit forces can cause the meter flanges to vibrate in the Y-direction. If this flange vibration is in-phase with that caused by the drive mass offset, then the balance mass can be increased to compensate for the additional vibration due to the manifold deformation. Likewise, if the flange vibration due to manifold deformation is out-of-phase with that caused by the drive mass offset, the balance mass can be  
15 made smaller.